hanging echo at high levels on the right forward flank (cf. fig. 5 of Browning [1]).[2]

Fujita also draws attention to a movement of the vault and its associated updraft toward the edge of the low-level echo during the development of the hook echo (cf. figs. 10 and 12 of Fujita [3]). As explained above, I do not believe that this is due to the differential motion of *two* distinct updraft areas as Fujita suggests; rather, I believe that it is better to regard this as being due to the anomalous motion of a single updraft area, with the relative winds in the environment carrying precipitation particles predominantly toward one side of it. Since the development of the hook echo is accompanied by a veering and a slowing down of the storm's velocity of travel, the relative winds carry this precipitation increasingly farther toward the storm's left forward flank during the development of the hook. Of course the important question remains as to why the intense updraft should change its direction of travel at all, and Fujita's Magnus hypothesis offers an interesting explanation of this.

3. The hook echo itself is an echo which extends part way around the vault at low levels. Fujita and I both attribute its development to the cyclonic turning of the streamlines at some level within the updraft. However, according to Fujita, the hook is composed of water droplets and other particles which are grown within the "major thunderstorm cell" and subsequently are drawn into the circulation of the updraft associated with the vault. In my view the particles comprising the hook echo, like those in the so-called major thunderstorm cell, have been grown within the primary updraft itself, around the vault at higher levels. Probably they differ from the particles descending ahead of the updraft in the "major thunderstorm cell" only insofar as they are larger and therefore fall closer to, or within, the intense updraft.

4. Since a large part of the radar echo may be associated with falling precipitation and downdrafts rather than with cloud and updrafts, and, moreover, since the echo-free vault is characterized by updrafts (and thus dense cloud) but no precipitation, it is clearly misleading to use the words "cloud" and "echo" interchangeably and to always identify updrafts with echo. The importance of this cannot be overemphasized.

[2] *Note added later:* In his reply Fujita mentions the existence of convergence at the surface beneath the major echo as evidence of updrafts within this echo. In my model, surface air beneath parts of the major echo actually enters the updraft within and around the vault, whereas subsiding air within the major echo at higher levels spreads rearward toward the area marked HAIL in figure 1 as it nears the surface, to some extent undercutting the intense updraft within the vault. The existence of streamers protruding beneath the base of the sloping overhang, as described by Browning and Donaldson [2] may be cited as evidence of the existence of relatively passive particle trajectories like TT within the major echo.

REFERENCES

1. K. A. Browning, "Airflow and Precipitation Trajectories Within Severe Local Storms Which Travel to the Right of the Winds," *Journal of the Atmospheric Sciences*, vol. 21, No. 6, Nov. 1964, pp. 634–639.
2. K. A. Browning and R. J. Donaldson, Jr., "Airflow and Structure of a Tornadic Storm," *Journal of the Atmospheric Sciences*, vol. 20, No. 6, Nov. 1963, pp. 533–545.
3. T. Fujita, "Formation and Steering Mechanisms of Tornado Cyclones and Associated Hook Echoes," *Monthly Weather Review*, vol. 93, No. 2, Feb. 1965, pp. 67–78

[*Received April 26, 1965; revised August 5, 1965*]

REPLY

TETSUYA FUJITA

The University of Chicago, Chicago, Ill.

About 10 years after the first hook-echo picture was obtained by the Illinois State Water Survey back in 1953, at the Urbana meeting both Browning and I presented two independent papers dealing with the nature of hook-echo circulations derived mainly from intensive studies of several hook echoes which occurred in Oklahoma on May 26, 1963. Despite the fact that the observational evidences are still far from sufficient for the establishment of a realistic model, Browning and I are in agreement with regard to various aspects which are not included in his comments.

The terms "eye" (Fujita) and "vault" (Browning) discussed by Browning in the first comment are still subject to debate and it is very likely that he and I are using these terms to designate different portions of a circulation made visible by a hook-shaped PPI echo. In my definition the "eye" designates the echo-free area Y (fig. 12 of Fujita's [1] paper) around the axis of circulation. Browning's "vault" (fig. 1 of Browning's comment) includes a much larger area surrounded by the hook and the major echo. In order to generalize my statement, several examples of other PPI photographs are presented in figure 1. I feel that the mechanisms of such eye (not vault) formation are very similar to those of a hurricane eye, although they are not identical, of course. If we assume that the inflow motion takes place under the influence of surface friction, the absolute circulation around the eye is smaller than that integrated around the outer regions of the storm since we expect certain frictional dissipation of angular momentum.

It is amazing to see, however, that the tangential winds inside both dust devils and hurricanes, 100,000 times larger in horizontal dimensions, can be approximated as solid rotation cores surrounded by irrotational vortices. Thus,

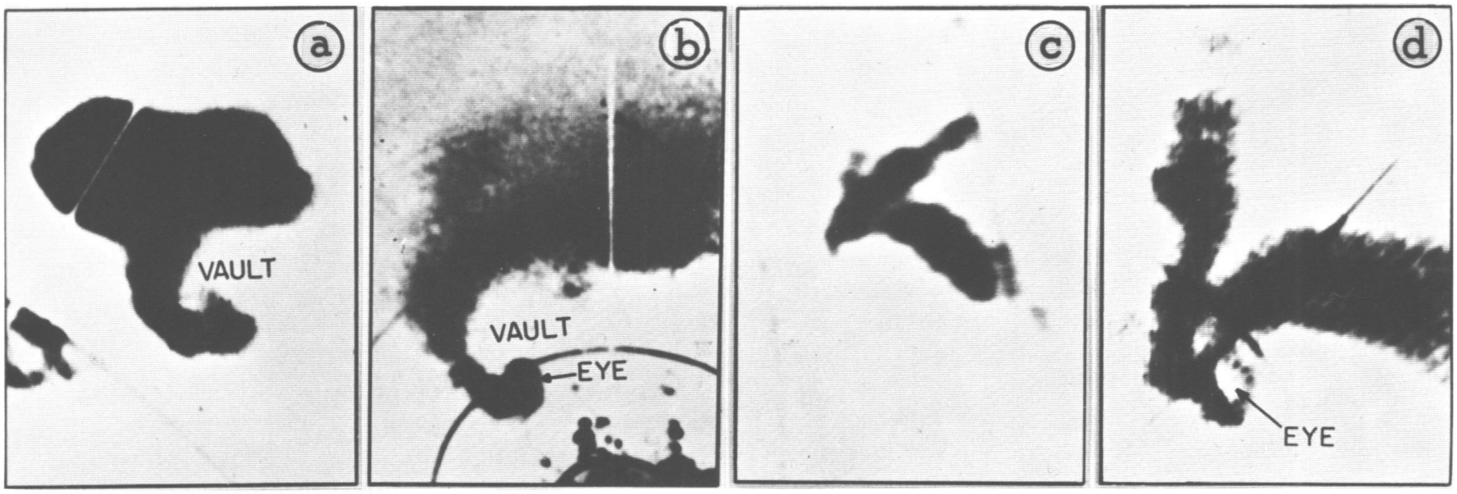

FIGURE 1.—Examples of echoes with rotational characteristics accompanied by tornadoes. (a) Tornadic storm south of Chicago, July 22, 1963. (b) Northeastern Kansas tornadoes of May 19, 1960. (c) Palm Sunday Indiana tornadoes of April 11, 1965. (d) Illinois tornado of April 9, 1963.

the inflowing surface air moves upward as its tangential velocity increases more or less inversely proportional to the radius until a maximum value is reached. The diameter of such a circular area surrounded by maximum winds depends upon the absolute circulation, the roughness of the surface, moisture and heat transfer from below, dry and moist adiabatic processes of rising air, thermodynamical stability, etc. Inside the circle of maximum winds the vertical motion rapidly drops off toward the center and there will be a weak either upward or downward motion at the center. I agree that Browning's *vault* is characterized by an intense updraft, but the updraft inside the *eye* should not contribute more than a fraction of the total vertical circulation of the storm because of its weak vertical motion and its small diameter ranging from one to a few miles. Instead, the major influx, in terms of vertical motion and its area, takes place within the inner portion of the vortex surrounding the eye. Note that Browning's "vault" includes this region of major influx.

The vertical extent of the eye depends upon the stage of formation and also the intensity of the circulation. When an updraft with straight radial convergence at low levels first starts sucking up low-level air with rotational characteristics, cyclonic or anticyclonic, the angular momentum of the ascending air will quickly dissipate because of the frictional drag of the non-rotating atmosphere surrounding the newly developing rotational field. By the time the new updraft reaches a certain level its angular momentum may be lost completely, thus changing into a straight updraft. Through a process similar to the development of orographic cumuli, the successive rotating updrafts will extend higher and higher since the earlier ones modify their environments. Although both Browning and I did not find the echo-free area all the way to the top, it is certainly feasible that the top T in figure 12 of

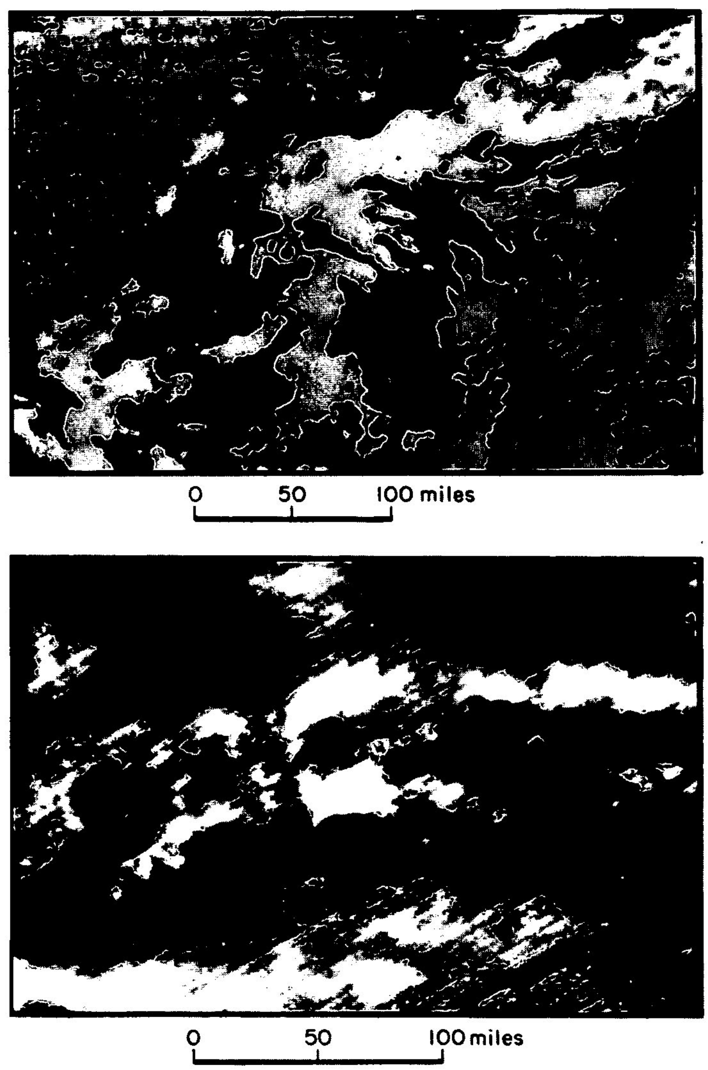

FIGURE 2.—(a) Clouds with rotational characteristics seen in Nimbus APT picture. (b) Hook-shaped clouds along a warm frontal zone of typhoon Bess (TIROS picture).

Fujita's [1] paper flattens out in the mature stage. When the circulation at the higher levels intensifies gradually, a rotating feature may appear at the cloud top and could be visible from a high-flying jet. In fact there are several cases of vortex patterns seen from jets flying above the top of intense thunderstorms. Through radar observations we often see that a hook (figure 1 a or b) changes into a bird (c) or spiral (d) as the circulation intensifies with time. In such cases the system is characterized by a so-called tornado cyclone or mesocyclone, thus necessitating the converging surface air to spend a considerably long time before reaching the innermost portion of the vortex. We may then see a rain-band type echo with slightly large crossing angles and a small eye in the echo.

It might be of interest to present TIROS and Nimbus pictures taken over the area of highly vortical fields. A Nimbus APT picture (fig. 2a) obtained at the Chicago Weather Bureau indicates several holes in clouds some of which are distributed along spirals representing a cyclonic circulation. Another example (fig. 2b) shows convection clouds developed along a warm front or shear line which were intensifying as typhoon Bess, south of Japan, moved northward. A large number of hook-shaped clouds are found in the picture. As a result of these evidences I am using the term "eye" to designate the hole when it appears near the end of a hook. The eye may be closed or may not be seen in certain stages of development especially when a PPI antenna is raised beyond certain limits. There are cases where hurricane eyes are closed at the tops by dense cirrus clouds. Calling such a cloud- or echo-free region at the vortex center an "eye" implies dynamical, thermodynamical, and physical processes giving rise to its formation and subsequent development.

It is important to realize, however, that the "eye" is not located at the geometric center of a circle drawn to fit the curved finger which merely represents a spiral characterized by a large crossing angle. As a conclusion, I have no objection to using the terms "vault" and "eye" separately under the complete understanding as to what they represent. They should not be used interchangeably since the regions designated by these terms are different and rather hard to distinguish when the end of a hook does not wrap around a core circulation.

In answering Browning's second item, the term "vault" should be understood as "eye" whenever it is referred to in my paper. I do not intend to clarify the reason for using the word "parent" or "mother" since many people are using them in the sense that the thunderstorm cell, rather than the hook echo, is the one which produces tornadoes. More important is the difference of opinion on the region or regions of updraft. Here again we have to learn more about the evolution of the entire circulation, both horizontal and vertical.

In the early stage of development of the horizontal circulation its area is so small that the non-rotating updraft will be a major contributor to the energy budget. As the rotation intensifies, it is, of course, natural to observe intense updraft around the core circulation, but it is difficult to agree that the entire region of the major echo is predominantly a region of downdraft. Detailed mesoanalysis of surface winds beneath the major echo indicates the existence of significant *divergence* beneath the region indicated as HAIL in Browning's figure 1. Appreciable *convergence* of the order of 10 to 30×10^{-5} sec.$^{-1}$ dominates the region covering the eastern half to three-quarters of the echo. Such a convergence is comparable to that observed beneath moderate to intense cells without rotation.

When the horizontal circulation becomes sufficiently intense the echoes within the mesocyclone or tornado cyclone display definite spiral curvature and the number of spirals increases from one to two or more. Especially the one extending to the north or northwest quickly takes a cellular structure and in some cases new cells grow in the upwind side of the old ones. After reaching this stage the mesocyclone is so intense and large in horizontal dimensions that the system cannot be described simply as a rotating cloud but as a convection inside a tornado cyclone. It should be noted that a tornado is often found in this stage (fig. 1 c and d). The low-level air flowing into this mesocyclone is convergent as a result of the surface friction and pressure gradient force, and the updraft is certainly capable of rising through the hydrometeors as long as their drag is not sufficient to kill the vertical motion.

In my explanation of the differential motion of the rotating updraft relative to the straight updraft, the "Magnus" force tends to pull the central core circulation in the direction perpendicular to the general flow. This is not simply a consequence of the relative wind in the environment. We must realize, however, that a veering and a slowing down of the translational velocity of a hook-echo circulation is required to initiate the relative wind. Consequently, the reasons for such a velocity change should be explained first (see fig. 10, Fujita [1]). Unless somebody else comes up with a better explanation, I prefer to relate the slowing motion with the intensification of updraft or increasing vertical mass transport, and the veering motion with the Magnus force. That is to say, the rotating updraft, more intense than its environment, first slows down the traveling speed, thus resulting in a faster motion of the environment. The Magnus force, proportional to the product of the circulation and the relative translational speed, then pulls the vortex either right or left depending upon the cyclonic or anticyclonic rotation. While such a separation of old echo and new rotating updraft is in progress the rotating updraft intensifies and the old updraft may weaken. This does not mean that we should consider only one region of updraft near the core circulation while eliminating other regions of updraft inside the entire vortex the diameter of which may increase appreciably with time. I presume that the contribution of updraft around the core circulation to the entire vertical circulation of a mesocyclone is most significant in some stages of the storm's development but the same is not true at its initiation and mature and post-mature stages of circulation.

Browning's third comment is closely related to the previous one which involves time elements and a difference of opinion. To clarify this problem, therefore, it is necessary to define the stages of the storm's development. When a rotating updraft starts forming, its vertical extent is so low that most of the particles around the eye would be coming from the major or old cell (fig. 1a). As time passes, the particles grown within the rotating updraft around the eye will contribute more but not necessarily 100 percent. It is usual to see one or two small echoes some 30 mi. away to the southwest quickly converge toward the core circulation until they are absorbed into the vortex. On the contrary small cells within 5 or 10 mi. to the north of the eye move northeast showing signs of intensification. These phenomena are frequently observed after a mesocyclone circulation has been well established.

I agree entirely with the last comment since it emphasizes the difference between the words "cloud" and "echo." I would rather generalize this problem so that the outer boundary as well as the energy received by a receiver (sensor for infrared, photometer for light) should be expressed as a function of wavelength of electromagnetic waves. We know that cirrus cover, when determined by infrared, is much larger than visually determined cloud covers. Within the range of microwaves the echo patterns change considerably according to wavelength and gain setting. I also agree that we should not identify updraft with echo, since echo simply means return from backscattering particles falling through the atmosphere which may be either moving upward or downward. A well-known report [2] includes many illustrations of up- and down-draft cells determined by airplanes and related to PPI echo patterns.

I believe that Browning's comments and my reply may stimulate more basic research on tornado-producing systems attracting more meteorologists who are specialized in thermodynamical, dynamical, and physical problems in the mesoscale atmosphere. At the same time, we have to obtain three-dimensional winds in and around such storms by means of either direct or indirect measurements, in order to understand these storms more completely.

REFERENCES

1. T. Fujita, "Formation and Steering Mechanisms of Tornado Cyclones and Associated Hook Echoes," *Monthly Weather Review*, vol. 93, No. 2, Feb. 1965, pp. 67–78.
2. H. R. Byers and R. R. Braham, *The Thunderstorm*, U.S. Weather Bureau, Washington, D.C., 1949, 287 pp.

[*Received June 15, 1965; revised August 9, 1965*]